Airflow Design for Cleanrooms and its Economic Implications

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Introduction

A cleanroom is designed to control the concentration of airborne particles. As a result, large amount of cleaned air is often required to remove or dilute contaminants for satisfactory operations in critical cleanroom environment. Cleanroom environmental systems (HVAC systems) in semiconductor, pharmaceutical, and healthcare industries are much more energy intensive compared to their counterparts (HVAC systems) serving commercial buildings such as typical office buildings. There is a tendency in cleanroom design and operation, however, to provide excessive airflow rates by HVAC systems, largely due to design conservatism, lack of understanding in airflow requirements, and more often, concerns such as cleanliness reliability, design and operational liabilities. A combination of these likely factors can easily result in HVAC systems' over-design.

Energy use of cleanroom environmental systems varies with the system design, cleanroom functions, and critical parameter control including temperatures and humidities. In particular, cleanroom cleanliness requirements specified by "cleanliness class" [1],[2] often cast large impact on energy use. A review of studies on cleanroom operation costs indicated that energy costs could amount to 65-75% of the total annual cost associated with cleanroom operation and maintenance in some European countries[3]. Depending on cleanroom cleanliness classes, annual cleanroom electricity use for cooling and fan energy ranged approximately between 1,710 kWh/m^2 and 10,200 kWh/m^2 (or 160 kWh/ft^2 and 950 kWh/ft^2) in California[4], USA. Cleanroom fan energy use typically consumed half of total HVAC energy use in three states in the USA[5]. For cleanrooms in a wafer-process semiconductor factory in Japan[6], HVAC systems used 43% of power consumption of an entire cleanroom factory, while air delivery systems account for 30% of the total power consumption. Fan energy use for cleanrooms of ISO Classes 3,4,5 collectively account for approximately 80% of the fan energy use for cleanrooms of all classes[7]. It is evident that biggest factors dictating cleanroom operating energy costs often include the magnitude of cleanroom airflow and how efficiently the HVAC systems deliver the cleaned and conditioned air to cleanrooms.

Since energy generally represents a significant operating cost for cleanroom facilities, improving energy efficiency in cleanrooms can potentially contribute to significant cost savings. Because the number of cleanrooms in the world has been growing rapidly in the last decade and involves many industries, improvement in energy efficiency is becoming more important. Even during economy downturns, with industry profit margins lessening, the ratio of cleanroom energy costs to a company's profits naturally increases. This can lead to a higher return of investment if cleanroom owners and engineers effectively take appropriate energy efficiency measures. While effective contamination control is the main purpose to operate a cleanroom, how to achieve efficient contamination control operations in cleanrooms presents constant challenges to many engineers in the industries. This paper examines how the real environmental systems in ISO Cleanliness Class-5 cleanrooms actually performed, in terms of airflow and energy use required by fan systems, and presents opportunities and benefits in energy efficient cleanroom designs.

Objectives

The objectives of this paper are to 1) present performance analysis for HVAC systems in seven ISO Cleanliness Class-5 cleanrooms; 2) identify ways to increase cleanroom energy efficiency, while achieving effective cleanroom contamination control; and 3) illustrate benefits of energy efficient cleanroom designs.

Approaches

The HVAC systems for ISO Cleanliness Class-5 cleanrooms, which correspond to Cleanliness Class 100 cleanrooms according to Federal Standard 209E[8], are selected because cleanrooms of ISO Cleanliness Class-5 belong to the types that likely have the most energy-intensive HVAC systems serving cleanrooms. The main technical approach is to analyze performance of actual HVAC systems serving seven ISO Cleanliness Class-5 cleanrooms, and to capture opportunities in cleanroom design for efficiency. Because Federal Standard 209E was cancelled not long ago, the industry is still in the transition of adopting the new ISO cleanliness classification. This paper will use ISO Cleanliness Classes however in the following discussion unless otherwise noted. In addition, a review of related literature is included to shed some light on cautions and implications when following cleanroom design guides. The main metrics discussed in this paper include the following: 1) Energy Efficiency of a Supply Air Handler Unit; 2) Average Cleanroom Air Velocity; and 3) airflow to cleanroom in terms of Air Change Rate. Specifically,

- Energy Efficiency of a Supply Air Handler Unit is defined as the total airflow rate per unit of total electricity input (kW) for all recirculation air fans (m^3/kWh, or cfm/kW);

- Average Cleanroom Air Velocity is defined as the total circulation airflow rate divided by primary cleanroom floor area (m/s, or fpm); and

- Air Change Rate is defined as the total circulation airflow rate divided by primary cleanroom volume (1/hr).

The majority of the energy use in cleanroom HVAC systems is associated with the recirculation systems and often to a lesser degree, the make-up air and exhaust systems. The air systems recirculate clean conditioned air through high efficiency particulate air (HEPA) filters for cleanrooms. The air systems discussed in this paper include three common designs as the following:

- Type I: Fan-tower with pressurized-plenum;

- Type II: Distributed recirculation air handler unit; and

- Type III: Fan-filter unit.

Airflow Design

A successful airflow design has two folds of meanings: effective contamination control in the cleanroom, and efficient air delivery to the cleanroom. To maintain effective contamination control for a particular cleanroom, large quantity of cleaned air is often needed. The following are the major factors determining the air system efficiency: cleanroom activities (e.g., process, cleanliness class), airflow rate, airflow distribution (e.g., re-entrainment, uniformity), particle size, particle transport rate, and HVAC equipment and components (e.g., filter efficiency). Based upon the analysis of the energy efficiency of actual air handler units (AHUs) and cleanroom airflow, the following analyzes the factors that influence the energy efficiency of a cleanroom HVAC system, and illustrate implications for an energy efficient airflow design.

Energy Efficiency of Supply Air Handler Units

The types of recirculation systems, design details, and layout can largely affect the magnitudes of overall air system efficiency. The bottom line is that reducing resistance in the air path throughout air systems can lower pressure drops, and thus require less fan power and energy to recirculate the air needed to maintain effective contamination control. Figure 1 shows the energy efficiency of different types of recirculation air systems used to recirculate clean conditioned air for the seven ISO Class-5 cleanrooms. Overall, the system efficiency varied dramatically from cleanroom to cleanroom. For

example, energy efficiency of Type I recirculation air systems ranged from 8,300 m^3/kWh to 17,400 m^3/kWh (or about 4,900 cfm/kW to 10,100 cfm/kW), which was generally far more efficient than its counterpart of other types of recirculation air systems (i.e., Type II and Type III). Compared to a study by Grout[9], Type II and Type III units in this study were rather energy inefficient. Overall, the lower energy efficiency illustrated in Type II and Type III systems was likely due to a combination of inefficient HVAC components (e.g., filters, motors), inefficient design, and a lack of efficient layout of the recirculation air pathways. Based on the performance data and the analysis, it is important that the planning and design of a cleanroom should provide necessary space and appropriate adjacencies for efficient air systems, and should thoroughly consider applicable types of recirculation air systems, and using energy efficient components.
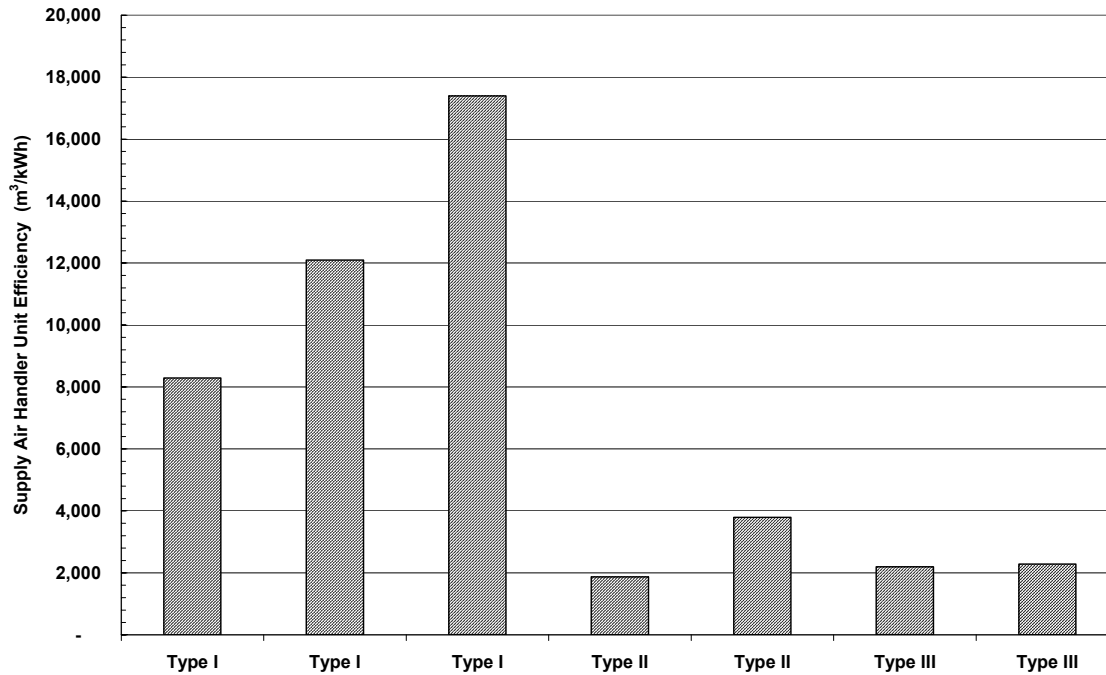
Figure 1. Energy efficiency of recirculation air systems

## Cleanroom HEPA Filters and Ceiling Coverage

The air systems recirculate conditioned air through HEPA filters for cleanrooms. Depending on the system types, a pressurized plenum or ductwork is connected to HEPA filters in the ceiling. On one hand, HEPA filters have different levels of filter efficiency and effective areas that are less than their actual physical sizes; on the other hand, the ceiling coverage by HEPA filters varies with design requirements. Often, the ceiling coverage by HEPA filters can be anywhere between 25% up to 100%. With lower ceiling coverage, the face velocity of airflow in the filter would tend to be higher, resulting in more fan power demand. Careful considerations should be given when selecting filter efficiency and space layout.

Cleanroom Airflow

Simply relating a cleanliness class level to a specific cleanroom air velocity or air change rate is a prohibitively complex and sometimes contradictory task due to numerous factors involved. Regardless of air distribution, more air alone may not necessarily be better in terms of the effectiveness of contamination control.

ASHRAE[10] indicates that recirculation airflow rates around 90 cfm per square foot, which equals the average cleanroom air velocities around 0.46 m/s (or 90 fpm) with a full ceiling coverage, are usual for ISO Class-5 or cleaner

cleanrooms. The IEST Recommended Practice RP-CC-012.1 – "Considerations for Cleanroom Design" recommends a range of air change rates between 240 and 480/hr for ISO Class-5 cleanrooms for common airflow patterns, which correspond to cleanroom air velocities between 0.20 m/s and 0.41 m/s (or 40 fpm and 80 fpm) for any airflow pattern (unidirectional, non-directional and mixed)[11] assuming a full ceiling coverage. A study [12] recommended 0.36-0.51 m/s (or 70-100 fpm) for cleanrooms of ISO Class-1 through Class-5, and provided a lower range of air change rate (up to 275/hr) for ISO Class-5 through Class-8 cleanrooms. Recent development in updating the IEST RP-12.1[13] proposed that air change rate should be over 200/hr for non-unidirectional airflow for ISO Class-5 and 6 cleanrooms, while cleanroom air velocity should be between 0.20 m/s and 0.50 m/s (or, 39 fpm and 98 fpm) for unidirectional airflow for ISO Class 5 and cleaner cleanrooms.
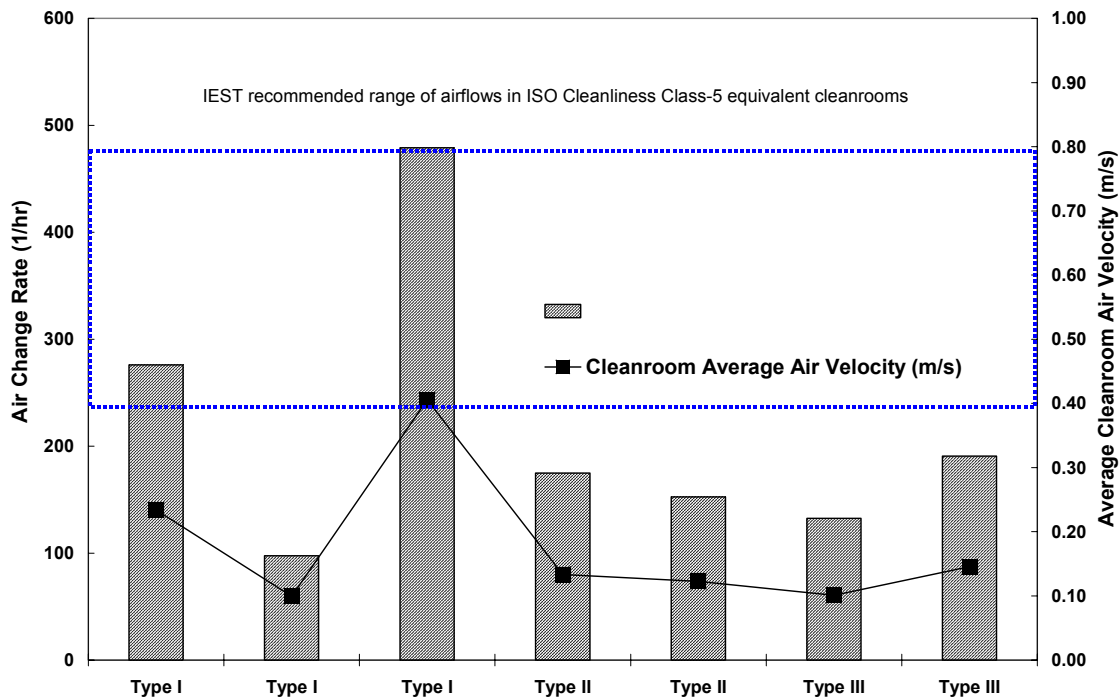
Figure 2. Actual recirculation air change rates and cleanroom air velocities

vs. IEST recommended ranges[11]

Figure 2 shows the actual air change rates and average cleanroom air velocities for the cleanrooms measured in this study. The measured air change rates ranged approximately from 100/hr to 480/hr, corresponding to average air velocities between 0.10 m/s and 0.41 m/s (or 20 fpm and 80 fpm). This indicates that there was a large variation in recirculation air supply among different systems, depending on design, layout, and cleanroom activities. This also shows that providing good airflow distribution, even airflows with an average cleanroom air velocity of as low as 0.10 m/s can effectively dilute or transport particles away effectively. The sparkling contrast is that the majority of the air change rates fell far below the recommended lower limits (e.g., 0.46 m/s, or 90 fpm in ASHRAE[10]; 240/hr in IEST RP-CC012.1[11]) or the new IEST's proposed revisions (i.e., lower limit of 200/hr or 0.20 m/s[13]).

Design opportunities for HVAC energy efficiency and savings can very well exist in cleanroom practice. Increasing the recirculation air supply than actually needed will result in much larger fan power required and therefore operating costs. For example, an additional 20% to 50% airflow supply would increase recirculation fan power by approximately 70 to 240%. Furthermore, the increase of fan power use to re-circulate cleanroom air would also adversely increase additional cooling load due to extra heat generated from fan operation. The airflow design specifications for cleanroom systems will dictate sizes of whole HVAC systems, including their initial costs and related capitals.

It is clear that careful design for energy efficient air systems plays a significant role in systems' investments. It is important for designers *not* to specify excessively higher cleanroom airflow supply than is needed for a specific cleanroom process. Another implication is that the relevant design guidelines be followed *only* with a grain of salt.

Economic Implications

It costs a lot of money to move air for cleanroom environment. There has been tendency in practice to jack up air velocities to lower particle counts. There were however, cases that higher cleanroom air velocities increased the particle counts in the test area, while lower velocities decreased the particle counts at the work areas[14]. The initial costs of HVAC equipment and subsequent operational costs are dictated by design airflows and design loads; therefore, it is very important to evaluate design parameters, especially to determine appropriate airflow rates.

Cleanroom HVAC systems account for a large percentage of energy costs. Depending on cleanroom cleanliness requirement, cleanroom size, system design and utility rates, the costs may vary significantly. To illustrate the operation cost impact of a recirculation air system, Figure 3 shows the fan kWh costs for cleanrooms. Based upon various system energy efficiencies, the figure is associated with an assumed airflow of 1,000,000 m^3/h (or about 583,000 cfm), operating 24 hours a day for the whole year (8,760 hours), and a utility rate of $0.065 per kWh. The annual fan kWh costs alone for the cleanrooms with less efficient AHUs can easily be over quarter million US dollars. Significant cost savings in operating the cleanrooms could be realized by an increase in recirculation system efficiency for cleanrooms.

The key to an energy efficient air management system is that designers should carefully consider initial costs, operating costs, process loads, and requirements for high cleanroom performance and effective contamination control. For example, the most efficient pressurize-plenum may require additional space. It may also require noise control, which would increase air system static pressure and thus increase the fan power. So comparing these undesired consequences against the efficiency gains from the selection of an efficient plenum system is the challenge. Another example is that fan-filter units exist that are more efficient than those tested in the study. They come with electronically commutated DC motors and can significantly reduce the operating cost over their lifetime.
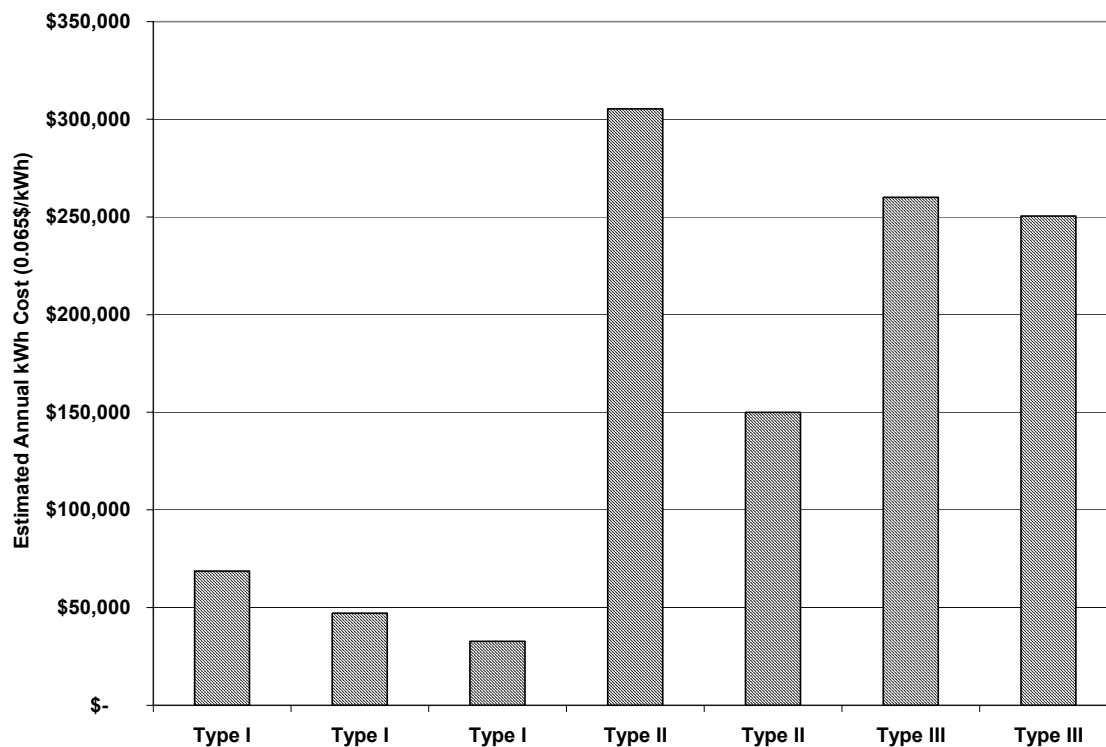
Figure 3 Annual fan kWh cost of recirculation air systems for 1,000,000 m^3/kWh cleanrooms

Conclusions and Recommendations

A high performance cleanroom should be not only an effective cleanroom in terms of contamination control, but also an efficient cleanroom in terms of energy performance. An efficient airflow system will help the cleanroom achieve high performance and contribute to the business bottom lines in cleanroom industries.

Designing an appropriate amount of recirculation airflow is critical to the satisfactory performance of cleanroom environmental systems, as well as to effective contamination control. It is important for designers *not* to specify excessively higher cleanroom airflow supply than necessary for a specific cleanroom process. Carefully arranging cleanroom systems and process layouts can have lasting impacts on energy use of air systems. In general, air systems with lower pressure drops (lower resistance to flow) along air delivery paths have higher efficiency than those with higher air pressure drops. Existing design guidelines for airflow ranges should be followed *only* with a grain of salt. Improvement in energy efficiency in cleanroom systems while achieving effective contamination control will benefit industries by creating immediate capital cost savings as well as life-cycle savings, thus improve business bottom lines. The management in cleanroom industries should regard energy efficient design as a strategy to profit from energy cost savings as well as capital cost savings.

Acknowledgements

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